ADMINISTRATIVE INFORMATION

1. **Project Name:** Tunable Diode Laser Sensors for Monitoring and Control of Harsh Combustion Environments (DE-FC36-00CH11030)

2. **Lead Organization:** American Air Liquide
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5. **Date Project Initiated:** 05/01/2000

6. **Expected Completion Date:** 12/31/2004

PROJECT RATIONALE AND STRATEGY

7. **Project Objective:**

This project focuses on the development of a sensor system based on the use of tunable diode lasers for *in-situ* monitoring of key combustion species CO, O_2 and H_2O along with gas temperature in industrial furnaces. The non-intrusive nature of the technique is ideally suited for harsh high temperature environments with corrosive gases and/or high levels of particulate matter. The sensor is a crosscutting technology that is applicable for controlling the combustion space to achieve improved energy efficiency, reduced pollutants, and improved product quality. The project includes evaluation of the technology under simulated industrial conditions on a pilot furnace and industrial demonstrations on a steel reheat furnace, aluminum reverberatory furnace, and an electric arc furnace (EAF).

8. **Technical Barrier(s) Being Addressed:**

Currently, combustion space monitoring in harsh environments is limited to primarily extractive sampling systems using water-cooled probes and gas conditioning. This technology suffers from slow response times due to long sample lines, single-point measurement, and maintenance issues related to probe plugging and corrosion. The laser-based measurement being *in-situ* and non-intrusive addresses these issues. However, for the technology to become a viable sensor option the following technical barriers must be addressed:

- Identify an accessible high temperature spectra region for CO and H_2O monitoring.
- Develop a platform that minimizes the system complexity cost with minimum number of lasers and streamlined for wide wavelength range that allows O_2, CO, and H_2O detection from a single line-of-sight access point.
- Assess the level and frequency of maintenance required.
- Robust interface for industrial process monitoring.

- Immune to noise sources such as, mechanical vibration, EMI and EMF, beam steering, and background radiation

9. Project Pathway:

To overcome the technical barriers a progressive approach was adapted for development and evaluation. The initial steps consisted of identifying a spectral window accessible using standard telecommunication diode lasers suitable for the temperature and concentration range of interest. Following this step a prototype system was constructed along with launch and receiver modules having an optical layout for monitoring the broadly separated wavelengths required for simultaneous detection of CO, H_2O, and O_2. System evaluation was performed on a fully instrumented pilot scale furnace operating under simulated industrial conditions that include dynamic monitoring and injection of seed particles. These measurements set the groundwork for industrial demonstration of the technology under various process conditions on the steel reheat furnace and aluminum reverberatory furnace. This initial work helped in identifying additional technical barriers to address before installation and testing on the EAF.

10. Critical Technical Metrics:

Baseline metrics for off-the-shelve laser-based technology:

- Currently no commercial laser-based system suitable for EAF application
- Multiple systems required for CO, H_2O and O_2 monitoring impacting cost and complexity
- Limited temperature range offer

Project metrics:

- Multiple species detection system adaptable for different industries
- Large dynamic range ($1000<T<2000$ K)
- Autonomous operation
- Low maintenance (frequency $\leq$ 1 per month)
- Fast-time response (.2-1 Hz)
- Operational on high particle density processes (> 10 g/Nm^3)

PROJECT PLANS AND PROGRESS

11. Past Accomplishments:

The project is split between development and evaluation of the laser-based sensor under controlled conditions and industrial demonstrations that provide a more stringent evaluation of the technology for its measurement reliability, maintenance requirements, and measurement accuracy. For the development and evaluation phase of the program the following major milestones were achieved:

- Identified a spectral window monitoring CO and H_2O using a single DFB laser.
- Empirical calibration of the H_2O spectral features over a temperature range of 1100-2000 K.
- Launch and receive optical design adapted for O_2 (.76 μm) and CO/H_2O (1.5 μm) monitoring.
- Pilot furnace testing under simulated industrial conditions for dynamic monitoring and high particle density flows.
- Overall system hardening for EAF application
- Developed on-demand laser power control add-on option targeted for high particle density process monitoring applications.

For the industrial demonstrations the following milestones were achieved:

- Measurement demonstration on Charter Steel's 100 ton/hr reheat furnace performed near the billet surface in the soak and heat zones of the process. Dynamic variations in the temperature and O_2 concentration were observed as a function of the measurement distance to the billet surface. These measurements have potential impact for atmosphere control to minimize scale formation in addition to energy efficiency improvements.
- Aluminum reverberatory furnace monitoring demonstration performed on IMCO, Inc. 5000 lb/hr furnace. Measurements performed continuous over 8 days with no intervention near the molten metal bath surface. Process dynamics were captured and energy efficiency improvements performed resulting in 5% fuel savings.

12. Future Plans:

The major milestone to be accomplished is the final industrial test of the sensor on North Star Steel's electric arc furnace for real-time off-gas monitoring. This test consists of following three phases:

- Phase I is testing the standard sensor configuration for CO, H_2O, O_2 and gas temperature monitoring.
- Phase II consists of measurement enhancement techniques such as the on-demand laser power control to improve transmission through the high particle density gas stream, relax alignment issues, and improve background discrimination.
- Phase I and II will define the best configuration for a go/no go decision on a long-term phase III test. Here evaluation of the sensor for reliability, accuracy, and maintenance will be accessed to aid in defining a marketable product for EAF off-gas monitoring that can be coupled to a process control system.

Independent of the industrial test evaluation of a multi-section laser that provides an extended tuning range will be performed on laboratory burner and pilot furnace. From these tests, a go/no-go decision to transfer this technology into the prototype system for industrial on the EAF will be made.

13. Project Changes:

- Redirection of tasks due to laser supply issues
- Program extension with additional funding for new tasks (4/30/03 to 4/30/04)
- No-cost program extension (4/30/04 to 12/31/04)

14. Commercialization Potential, Plans, and Activities:

The technology developed is crosscutting applicable to many industries such as, secondary aluminum melting, steel processing, glass, waste incineration, etc. were combustion space monitoring of O_2, CO, H_2O and gas temperature can be used for process control to improve energy efficiency, reduce pollutants, and impact the product quality. For many of these industries conventional monitoring techniques are limited by the harshness of the environment and scale of the process.

For example, the electric arc furnace is a dynamic process with high particle densities and high temperatures. The non-intrusiveness of the laser-based sensor and fast-time response is ideally suited for capturing the process dynamics for use in optimizing the efficiency. In the United States, there are estimated 180 EAF furnaces. The vast majority of furnaces use no off-gas analysis due to the high maintenance and slow-response time of conventional technology. Successful implementation of this technology coupled with post-combustion control has a potential energy savings of 640,000,000 kW/year.

By the end of 2004, Air Liquide expects to have identified the key elements needed for providing a viable commercial offer to selected markets, e.g., EAF, that is tailored to the process needs and coupled with process control. In addition, integration of new emerging technology and exploring new applications will continue.

15. Patents, publications, presentations:

7 Patents submitted -

- Method for Continuously Monitoring Chemical Species and Temperature in Hot Process Gases
- Method for Enhanced Gas Monitoring in High Particle Density Flow Streams
- Method for Monitoring and Controlling High Temperature Reducing Combustion Atmospheres
- Apparatus for Launching and Receiving a Broad Wavelength Source
- Indirect Gas Species Monitoring Using Tunable Diode Lasers
- Wavelength Tuning Control for Multi-section Lasers
- Dynamic Laser Power Control for Harsh Processes and Distributed Gas Monitoring

8 Publications/Presentations -

- "*Tunable Diode Lasers Sensors for Industrial Oxy-fuel Combustion Monitoring"*, American Flame Research Committee, 2000 AFRC International Symposium, Newport Beach CA, to be presented September 2000.
- "*Multi-functional Industrial Combustion Process Monitoring with Tunable Diode Lasers",* SPIE The International Society for Optical Engineering, Environmental and Industrial Sensing, to be presented, Boston Massachusetts, November 2000.
- "*Tunable Diode Laser Sensor Characterization for Harsh Combustion Monitoring"*, 2001 Joint AFRC/JFRC/IEA International Combustion Symposium, Kauai, Hawaii, September 2001.
- "*Tunable Diode Laser Sensor for the Metal Processing Industry",* 41st Conference of Metallurgists, Montréal, Québec, August 11-14 2002
- "*Multiple Gas Species Detection using a Tunable Diode Laser Sensor for Combustion Process Monitoring",* American Institute of Chemical Engineers 2002 Annual Meeting, Sensors for Process Control and for the Chemical Industry I, Indianapolis, IN, November 3-8 2002
- "*Laser-Based Multiple Gas Sensor System for the Metals Processing Industry*", Industrial Heating, The International Journal of Thermal Technology, January 2003.
- *" Tunable Diode laser Sensor for Multiple Species Monitoring in Harsh Atmospheres",* SPIE International Symposium on Optical Technologies for Industrial, Environmental, and Biological Sensing, Providence, Rhode Island, October 27-30, 2003.
- "*High-temperature multiple species diode laser sensor",* Optical Society of America Topical Meeting, Laser Applications to Chemical and Environmental Analysis, Annapolis Maryland, February 9-11, 2004.